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ORIGINAL CONTRIBUTION

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Vegetable crop management strategies to increase the quantity of phytochemicals

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Summary *Background* Numerous epidemiological studies show an inverse association between vegetable consumption and chronic diseases such as different types of cancer and cardiovascular disease. Phytochemicals in vegetables are known to be responsible for this observed protective effect. Therefore, raising the levels of these health-promoting substances in vegetables and/or using phytochemicals as food supplements would be desirable especially since dietary behaviour and the suboptimal efficiency of diet campaigns in industrial nations of Northern Europe and North America have resulted in a relatively low increase of vegetable consumption. *Aim of the study* The aim of this paper is to suggest crop management strategies based on genotypic and ecophysiological effects for the production of vegetables enriched with phytochemicals which can be served as fresh market products or be used as raw material for functional foods and supplements. *Results* Crop management strategies, representatively given here with broccoli, cauliflower and radish, demonstrated that the contents of individual phytochemicals could be increased 10-fold in broccoli and cauliflower, and 2-fold in radish.

Key words phytochemicals – vegetables – crop management – broccoli – radish

Introduction

Consumers are becoming more health conscious and diet is increasingly being considered as an essential factor for positively influencing health [1]. Healthy diets have become a social trend in industrial countries [2], where an accepted estimate is that at least one third of cancer cases and up to one half of cardiovascular disease cases are related to diet [3]. Health-promoting characteristics in food are therefore increasingly demanded and included in the purchase decision by the discriminating consumer [4]. An EU-consumer survey revealed that 32 % of the consumers' purchase decisions are oriented by the health aspects of food [5]. Consumers additionally take supplements as a disease prevention measure, as compensation for low vegetable consumption [6].

Numerous epidemiological studies have found an inverse association between vegetable consumption and chronic diseases such as different types of cancer [7–9] and cardiovascular disease [e. g. 9, 10]. Phytochemicals have been demonstrated to be the active component responsible for this observed protective effect by several cellular and biochemical *in vitro* tests as well as animal experiments [11, 12]. In these experiments, individual phytochemical components and other substances like vitamins, such as ascorbic acid, tocopherol and folic acid were tested [11–13].

Generally, overall vegetable consumption in the industrial nations of Northern Europe and North America is on a relatively low level [14, 15] and well under internationally accepted recommended amounts (i.e. approx. 375 g vegetables/per day) advocated by, e.g. the World Cancer Research Fund/American Institute for Cancer Research, the Health Education Authority (UK), the German Nutrition Society, and the German Cancer Society. Reasons for the suboptimal efficiency of current diet campaigns may be consumer complacency with respect to their diet, low income or confusion in the interpretation of the diet message [16]. With regard to current dietary habits it would be desirable to either increase the contents of phytochemicals in fresh vegetables or enhance supplementation of phytochemicals by means of vegetable products to increase the intake of these health-promoting substances.

One way to enhance the intake of phytochemicals would be to increase their content in fresh vegetables by utilizing crop production practices, e.g. selection of species and cultivars, nutrition and water supply, production and harvest time. These vegetables could serve as fresh market products or as raw material for functional foods and supplements (e.g. vegetable extracts).

A prerequisite for the production of such products is the investigation of the interaction between the genotypic and ecophysiological effects and the formation of phytochemicals in vegetables. The influence of different food-processing technologies on the content of phytochemicals has been investigated in numerous studies. However, the ecophysiological effects on phytochemicals have been determined quite non-specifically in different growing seasons regarding only single phytochemicals and single crops [e.g. 17, 18]. The interaction between genotype and ecophysiological factors was hardly considered.

The aim of this paper is to suggest crop management strategies, representatively given here by three model crops, i.e. broccoli (*Brassica oleracea* var. *italica* Plenk), cauliflower (*Brassica oleracea* var. *botrytis* L.) and radish (*Raphanus sativus* L. var. *sativus*), based on genotypic and ecophysiological effects on the production of vegetables enriched with phytochemicals, served as fresh market products or used as raw material for functional foods and supplements.

Nature and occurrence of phytochemicals

Phytochemicals vary widely in chemical structure and function. They are grouped accordingly in carotenoids, phenolic compounds, glucosinolates, saponins, sulphides, phytosterols, phytoestrogens, monoterpenes and protease inhibitors. Phytochemicals have important functions in the interaction of plants with their environment, e.g. as feeding deterrents, pollination attractants, protective compounds against pathogens or various abiotic stresses, antioxidants or signalling molecules. Many phytochemicals are present in a wide range of vegetable crops, e.g. polyphenols and carotinoids, while some phytochemicals are distributed only among limited taxonomic groups (Table 1). For example, glucosinolates are only found in the cruciferous vegetables crops, whereas the occurrence of sulphides is restricted to the Liliaceae. Additionally, each plant species has a distinct profile of phytochemicals, also within a special phytochemical group, as exemplified by the glucosinolate pattern of Brassicaceae vegetables (Table 2). Most of the phytochemicals were found in every plant organ; however, the amount and the profile of the phytochemicals can vary greatly [e.g. 19]. For example glucosinolates are present in the radish root, but only a small amount was measured in the leaves (Krumbein, Widell and Schreiner, unpublished data 1998).

Nutritional physiology of phytochemicals

The major classes of phytochemicals with disease-preventing functions are antioxidants, blood pressure or blood sugar influencing substances, or agents with anti-carcinogenic, immunity-supporting, anti-bacterial, anti-fungal, anti-viral, cholesterol-lowering, anti-thrombotic or anti-inflammatory effects [20] (Table 3). Each class of these functional compounds consists of a wide range of chemicals with differing potency. For example, phytochemicals with antioxidant properties are carotenoids, phenolic compounds, protease inhibitors, sulphides and phytoestrogens [20–24]. Some of these phytochemicals are characterised by a broad spectrum of health-promoting functions, e.g. phenolic compounds and sulphides [21–24].

Fresh vegetables are naturally rich in phytochemicals. Epidemiological research during recent decades strongly supports a protective effect of enhanced consumption of fresh vegetables against cancer and cardiovascular disease.

Evidence for an association between vegetable consumption and chronic diseases

Numerous epidemiological studies concluded that a higher consumption of vegetables is associated consistently (but not universally for all cancer types) with a reduced risk of cancer. Fundamental meta-analyses in this field were carried out by Steinmetz and Potter [e.g. 7] and Block et al. [26]. A meta-analysis by the World Cancer Research Fund/American Institute for Cancer Research [8] provided convincing evidence for the inverse association between vegetable consumption and cancer risk. A protective effect of vegetable consumption against cancer was evident in 80 % of the epidemiological studies.

Epidemiological studies also revealed distinct associ-

Table 1 Major phytochemicals in commonly consumed vegetables

Botanical classification			Phytochemicals							
Morphology	Family	Species	Carotenoids	Polyphenols	Glucosinolates	Saponins	Sulfides	Phytosterols	Phytoestrogens	Monoterpenes
Root and bulb vegetables	Apiaceae [e. g. 20, 25, 34, 56]	Carrot	β-carotene, α-carotene	Anthocyanins (glucosides of cyanidin), phenolic acids (chlorgenic acid), coumarins	–	–	–	Sitosterol	–	Myrcene, α-pinene, limonene, terpinolene
	Brassicaceae [e. g. 20, 25, 32, 46, 53]	Turnip, radish, kohlrabi	–	Anthocyanins (glucoside of pelargonidin), phenolic acids (p-coumaric acid, caffeic acid, ferulic acid, sinapin acid)	Alkyl, alkenyl, aryl glucosinolates	–	–	Sitosterol, campesterol	–	X
	Liliaceae [e. g. 20, 25, 21]	Garlic	–	flavonoid glucosides (quercetin, kaempferol)	–	–	S-allyl-L-cysteinsulfoxide, diallyldisulfide, diallyltrisulfide	/	–	α-terpinolene α-pinene, α-terpinol, myretenal, myretenol, β-pinene, p-cymene
Leafy vegetables	Brassicaceae [e. g. 18, 23, 24, 25, 53, 56, 58]	Cabbage, Brussel sprouts, kale, pak choi, tai tsai, mustard spinach, tatsoi, mizuna mustard, mustard green	β-carotene, lutein, neoxanthin	Anthocyanins (glucoside of cyanidin), phenolic acids (neochlorgenic acid), flavonols and flavonoid glucosides (quercetin, kaempferol)	Alkyl, alkenyl, indole glucosinolates	–	–	Sitosterol, campesterol, brassicasterol	–	α -terpinene, 3-carene
	Liliaceae [e. g. 25, 34, 56]	Onion, leek	–	Anthocyanins (glucosides of cyanidin), phenolic acids (ferula acid), flavonols and flavonoid glucosides (quercitin, kaempferol, spiraeosid)	–	–	Thiosulfinate	Sitosterol, campesterol	–	/
Stem Vegetable	Liliaceae [e. g. 25, 57]	Asparagus	–	Anthocyanins (glucoside of cyanidin), phenolic acids (ferula acid, p-coumaric acid), flavonols and flavonoid glucoside (rutin, quercetin, kaempferol)	–	X	Dimethylsulfid, diallylsulfide	/	–	/
Immature flower vegetables	Brassicaceae [e. g. 24, 25, 32, 35, 39, 46, 56]	Broccoli, cauliflower	β-carotene, lutein (in broccoli)	Phenolic acids (neochlorgenic acid), flavonols and flavonoid glucosides (quercetin, kaempferol)	Alkyl, alkenyl, indole glucosinolates	–	–	Sitosterol, campesterol, stigmasterol, brassicasterol	–	X
Mature flower vegetables	Brassicaceae [e. g. 18, 35, 55]	Chinese broccoli, choi sum	/	/	Alkenyl glucosinolates	–	–	/	Lignans (secoisolariciresinol)	X

ations between cancer risk and certain vegetable families or categories [7, 27]. For example, a high consumption of tomato or tomato-based products – rich in carotenoids, especially lycopene and β-carotene – is consistently associated with a lower risk (RR ≤0.60) of different cancer types as shown by a meta-analysis [28], with the highest evidence being found for lung, prostate and stomach cancer. A new evaluation of the β-Carotene Retinol Efficiency Trial (CARET) data revealed that Brassicaceae vegetables were associated with a reduction of lung cancer (RR = 0.68) [29].

Also many epidemiological studies showed that a diet rich in vegetables may protect against cardiovascular disease [e. g. 10, 30]. Legumes seem to play a key role in human diet in preventing cardiovascular disease. Legume consumption was significantly and inversely associated with cardiovascular diseases and lowered the relative risk by about 11 %. Additionally, the risk of coronary heart disease was reduced by 22 % [31].

Table 1 *continued*

Botanical classification			Phytochemicals							
Morphology	Family	Species	Carotenoids	Polyphenols	Glucosinolates	Saponins	Sulfides	Phytosterols	Phytoestrogens	Monoterpenes
Mature fruit vegetables	Solanaceae [e. g. 20, 24, 25, 56]	Tomato, pepper, pepino, aubergine cape gooseberry	β-carotene, α-carotene, lutein, neoxanthin	Anthocyanins (glucosides of delphinidin in aubergine, flavonols and flavonoid glucosides (quercetin, rutin, luteolin)	–	–	–	Sitosterol, campesterol, stigmasterol	–	X
	Cucurbiaceae [e. g. 20, 25]	Watermelon, cantaloupe, squash, patisson, pumpkin, courgette	β-carotene, α-carotene, lycopin, violaxanthin	+	–	–	–	Sitosterol	–	/
Seed vegetables	Fabaceae [e. g. 20, 25, 55, 56, 57]	Legumes (pea, bean, soybean, lentil, peanut)	β-carotene	Phenolic acids (p-coumaric acid, caffeic acid, ferulic acid), flavonols and flavonoid glucosides (quercetin, kaempferol, myricetin)	–	X	–	Sitosterol, campesterol, stigmasterol	Isoflavones (genestein, daidzein, glycitein), lignans (secoisolariciresinol)	/

X Phytochemical group which is mentioned in the references without specific compound details; – not detected; + trace (< 1 mg 100 g^{-1} fresh matter); / no data available

Genotypic and ecophysiological effects on phytochemicals of vegetables

Genetic factors have a direct influence on all compounds of vegetables. Environmental conditions and physiological factors may modify the expression of the compounds, but the genetic background of the product is the major determining factor. The content of phytochemicals in vegetables depends both quantitatively and qualitatively on their genetic information. There are clear examples showing different phytochemical contents of different species of the same genus and of different cultivars of the same species. As exemplified by broccoli, the green spear type has higher contents of the anti-oxidative effective carotenoids lutein and β-carotene than the crown type and violet cultivars. This type effect is also mirrored by the concentration of chlorophyll a and b, pigments with anticancer properties [32]. Carrots also showed genotypic variations in carotenoid composition expressed by cultivars rich in α- and β-carotene or lycopene [33]. According to the colouration, radish cultivars differ in their anthocyanin content. In red coloured radishes, pelargonidin 3-sophoroside-5-glucoside is present, while cyanidin 3-diglucoside-5-glucoside is found in purple radish roots and white radishes contain only flavonols [34]. Moreover, the broccoli types differed in their content of glucosinolates [17, 32]. In contrast to the pigments, the green coloured crown type showed the highest glucosinolate concentration [32]. Regarding the glucosinolate pattern in broccoli and cauliflower, green pyramidal cauliflower (romanesco type), violet broccoli, violet and green cauliflower showed higher contents of indole glucosinolates than green broccoli, whereas the alkyl glucosinolate glucoraphanin was mainly found in green broccoli type compared with other broccoli and

Table 2 Distribution profile of the major glucosinolates in Brassicaceae vegetables

Botanical classification		% of major glucosinolates				
Morphology	Species	Alky glucosinolates	Alkenyl glucosinolates	Aryl glucosinolates	Indole glucosinolates	References
Root vegetables	Turnip (*Brassica rapa* L. ssp. *rapa*)	12 Glucobrasicanapin	30 Progoitrin	30 Gluconasturtiin		54
	Turnip (*Brassica rapa* L. var. *Teltow*)	18 Glucobrasicanapin	11 Progoitrin	46 Gluconasturtiin		54
	Radish (*Raphanus sativus* L. var. *sativus*)		> 90 Glucoraphasatin			46, 54
	Japanese turnip (*Brassica rapa* L. var. *rapifera*)		28 Gluconapin	19 Gluconasturtiin	27	53
Leafy vegetables	White cabbage (*Brassica oleracea* L. var. *capitata* f. *alba*)	25 Glucoiberin	22 Sinigrin		20	52
	Red cabbage (*Brassica oleracea* L. var. *capitata* f. *rubra*)	33 Glucoraphanin			26	52
	Savoy cabbage (*Brassica oleracea* L. convar. *Capitata* (L.) Alef. var. *sabauda* L.)	29 Glucoiberin			52	52
	Brussel sprouts (*Brassica oleracea* L. var. *Gommifera* DC)		34 Progoitrin 17 Sinigrin		32	25, 58
	Chinese cabbage (*Brassica rapa* var. *pekinensis*)		16 Glucobrassicanapin	14 Gluconasturtiin	38	52, 53
	Pak choi (*Brassica campestris* L. ssp. *chinensis* var. *communis*)		31 Gluconapin 23 Glucobrassicanapin		38	18
	Tai tsai (*Brassica campestris* L. ssp. *chinensis* var. *tai-tsai*)		29 Glucobrassicanapin 23 Progoitrin 12 Gluconapin		34	18
	Mustard spinach (*Brassica campestris* L. rapifera group)		28 Glucobrassicanapin	19 Gluconasturtiin	27	53
	Tatsoi (*Brassica campestris* L. narinosa group)		37 Gluconapin		20	53
	Mizuna mustard (*Brassica campestris* L. nipposinicia group)		70 Gluconapin			53
	Mustard green (*Brassica juncea* L. integlifolia group)		90 Sinigrin			53
Immature flower vegetables	Broccoli (*Brassica oleracea* var. *italica* Plenck)	47 Glucoraphanin			44	32, 39, 46
	White cauliflower (*Brassica oleracea* var. *botrytis* L.)	22 Glucoiberin	25 Sinigrin		39	35, 54
	Green cauliflower (*Brassica oleracea* var. *botrytis* L.)	21 Glucoraphanin	12 Progoitrin		55	35, 54
Mature flower vegetables	Chinese broccoli (*Brassica rapa* var. *alboglabra*)	27 Glucoraphanin	48 Gluconapin 16 Progoitrin			18, 35, 54
	Choi sum (*Brassica campestris* L. ssp. *chinensis* var. *utilis*)		40 Gluconapin 19 Progoitrin 19 Glucobrassicanapin		16	18

cauliflower types [35]. In radish, no cultivar differences in the glucosinolate pattern occur. The alkenyl glucosinolate glucoraphasatin was always the main glucosinolate present although in different concentrations [25]. At the cultivar level, there are also differences in the polyphenol composition affecting vegetable characteristics. In the case of lettuce cultivars, some were very poor in flavonoids and other phenolic compounds, whereas other types contained large amounts of flavonols and anthocyanins [36]. Based on our knowl-

Table 3 Phytochemicals with their disease-preventing functions

	Disease-preventing functions								
Phytochemicals	A	B	C	D	E	F	G	H	I
Carotenoids	●		●		●				
Phytosterols	●							●	
Saponins	●	●			●			●	
Glucosinolates	●	●						●	
Polyphenols	●	●	●	●	●	●	●		●
Sulfides	●	●	●	●	●	●	●	●	
Protease inhibitors	●		●						
Monoterpenes	●	●							
Phytoestrogens	●		●						
Chlorophyll	●								

according to [11–13, 20–25, 55, 56]
A anti-carcinogenic; *B* anti-microbial; *C* antioxidative; *D* anti-thrombotic; *E* immunity-supporting; *F* anti-inflammatory; *G* blood pressure influencing; *H* cholesterol-lowering; *I* blood sugar influencing

edge of genetic variation and its effect on various phytochemicals levels in vegetables, breeding and genetic manipulation hold significant promise for developing genotypes with increased phytochemical content and improved composition [37].

In addition to the genetic influence, ecophysiological factors such as the climate parameters of irradiation and temperature have a strong influence on the phytochemical composition of vegetables. Moreover, water and nutrition supply influence the content of several phytochemicals, but climatic and genetic variations often have larger effects than changes caused by water and nutrient management [38]. All factors are responsible for the wide variation in the formation and content level of phytochemicals at pre-harvest and varying phytochemical contents at harvest.

Irradiation intensity has a definite influence on flavonoid metabolism. Vegetables exposed to full sunlight have been demonstrated to contain more flavonoids than those grown in the shade [e.g. 24]. Generally, the glucosinolate content of broccoli and cauliflower is strongly influenced by the temperature and to a lesser extent by irradiation during plant development. Increasing irradiation combined with relatively low daily mean temperatures led to rising contents of the alkyl glucosinolates glucoraphanin and glucoiberin in green broccoli as well as in green and white cauliflower [32, 35, 39]. This climate effect was also observed for the indole glucosinolates, with the exception of white cauliflower. In contrast, the glucosinolate content of violet broccoli and violet cauliflower cultivars was nearly unaffected by temperature and irradiation [35]. The temperature effect on the glucosinolate level could be due to the increasing myrosinase activity at higher daily mean temperatures degrading glucosinolates [17]. Unlike the alkyl and indole glucosinolates in green broccoli and green and white cauliflower, the indole and alkenyl glucosinolates contents in radishes showed only relative moderate or slight irradiation and temperature dependency ($r^2 = 0.40$ and $r^2 = 0.23$, respectively) [40]. This restricted effect of these climate factors on the indole and alkenyl glucosinolates is presumably due to the fact that the radish root is only partly exposed to direct irradiation, and hence the irradiation influence was not sufficient to enhance the glucosinolate synthesis as found in broccoli and cauliflower. For white cabbage, this limited climate effect could also be confirmed for indole glucosinolates when comparing different growing periods, e.g. spring and autumn production [17]. As a head-forming vegetable, only the outer leaves of the cabbage are influenced by direct irradiation, which is comparable to the partial irradiation of radish roots, and hence, this also results in a restricted climate effect. Moreover, various ecophysiological responses may also be the result of different biosynthetic pathways for the numerous glucosinolate groups. The glucosinolate groups derive from different amino acids and have various aglucon structures, which might lead to a diverse sensitivity to temperature and irradiation between the glucosinolate groups [40]. In contrast to the flavonoids and glucosinolates, irradiation is not essential for inducing carotenogenesis [41], and hence irradiation does not influence carotenoid biosynthesis, but is strongly temperature-dependent. For example, daily mean temperatures below 16.5 °C were beneficial for the β-carotene synthesis in broccoli [42], whereas the best temperature was 18 °C for carrots [43]. Beneficial temperatures for lycopene formation in tomato were found in the range from 16 °C to 21 °C [41].

A reduced water supply could lead to increased contents of phytochemicals. For instance, in the case of broccoli, less irrigation caused the glucosinolate content to double [44]. Mineral nutrients have specific and essential functions in plant metabolism. Numerous investigations have resulted in recommendations for a nutrient supply to enhance the compound yield in vegetables. However, new aspects have arisen in the context of sulphur application. Owing to the drastically decreased industrial SO_2 emissions, sulphur deficiency is becoming more widespread in agricultural areas of Northern Europe. However, enhancement of health-promoting sulphides and glucosinolates as sulphur-containing compounds is possible via increased sulphur supply. Increased sulphur application was related to an increasing alliin content in garlic and onion due to the enhanced formation of sulphur-containing amino acids as precursor of alliin [45]. Rising levels of sulphur have also led to increased glucosinolate contents mainly because of glucoraphanin in broccoli and glucoraphasatin in radish [46]. Decreasing nitrogen supply has promoted rising amounts of glucosinolates [44, 46], presumably being caused by an enhanced non-protein sulphur content, and hence in an increased availability of methionine [47]. In contrast, enhanced nitrogen application increased the formation of carotenoids and chlorophylls [46], whereas it might reduce the content of phenolic compounds [48].

Vegetable crop management strategies

Numerous studies on single crops and single phytochemicals have demonstrated that pre-harvest variables, such as type and variety selection as well as ecophysiological effects during the production process are factors that have the potential to influence the phytochemical content in vegetables [e. g. 42]. For a systematic approach regarding genotypic and ecophysiological effects on the formation of phytochemicals, three model crops of the economically important Brassica family were chosen for detailed investigations (Table 4). Broccoli and cauliflower are important representatives of the immature flower crops, and radish is also a highly demanded vegetable, but belonging to the root crops. Because numerous phytochemicals are present in a wide

Table 4 Effects of crop management parameters in the investigated vegetable crop managements

Crop management parameters	Phytochemicals	Model crops		
		Broccoli	Cauliflower	Radish
Genotypic effect	Glucosinolates	↑ indole glucosinolates: violet broccoli ↑ alkyl glucosinolates: green broccoli	↑ indole glucosinolates: violet and green cauliflower	↔
	Carotenoids	↑ lutein, β-carotene: spear broccoli	/	–
	Anthocyanins	–	–	↑ pelargonidin: red radish ↑ cyanidin: purple radish
Ecophysiological effects				
Daily mean temperature	Glucosinolates	↑ total glucosinolates: low temperatures (about 14 °C)	↑ total glucosinolates: low temperatures (about 14°C)	↔
	Carotenoids	↑ lutein, β-carotene: low temperatures (about 14 °C)	/	–
	Anthocyanins	–	–	↑ total anthocyanins: low temperatures (about 11 °C)
Daily mean irradiation	Glucosinolates	↑ total glucosinolates: high irradiation (about 450 μmol $m^{-2}s^{-1}$)	↑ total glucosinolates: high irradiation (about 450 μmol $m^{-2}s^{-1}$)	↔
	Carotenoids	↔	↔	–
	Anthocyanins	–	–	↑ total anthocyanins: high irradiation (about 450 μmol $m^{-2}s^{-1}$)
Sulphur supply	Glucosinolates	↑ alkyl and indole glucosinolates: 600 mg S per plant	/	↑ alkenyl glucosinolates: 30 mg S per plant
Nitrogen supply	Glucosinolates	↑ total glucosinolates: reduced N supply	↑ total glucosinolates: reduced N supply	↑ total glucosinolates: reduced N supply
	Carotenoids	↑ lutein, β-carotene: increased N supply	/	–
	Anthocyanins	–	–	↑ total anthocyanins: reduced N supply
Water supply	Glucosinolates	↑ total glucosinolates: reduced water supply	↑ total glucosinolates: reduced water supply	↑ total glucosinolates: reduced water supply
Cultural practice				
Production time	Glucosinolates	↑ total glucosinolates: spring and autumn	↑ total glucosinolates: spring and autumn	↔
	Carotenoids	↑ lutein, β-carotene: spring and autumn	/	–
	Anthocyanins	–	–	↑ total anthocyanins: spring, summer and autumn
Amino acid application	Glucosinolates	↑ alkyl glucosinolates: methionine	/	↑ alkenyl glucosinolates: methionine
	Anthocyanins	–	–	↑ anthocyanins: leucin, valin, phenylalanine
Developmental stage	Glucosinolates	↑ indole glucosinolates: incompletely developed head	/	↔

↑ increased content; ↔ no effect; – phytochemical is not in the vegetable; / not investigated range of plant organs and the formation of phytochemicals greatly differs between the plant organs [18], crops with different plant organs for consumption were also an aspect of selection.

To satisfy the increasing health consciousness of the consumers, the demand of vegetables enriched with phytochemicals available as fresh market products or raw material for functional foods and supplements has to be fulfilled. Thus, a consumer-oriented quality production of broccoli, cauliflower and radish has to be integrated into a total quality management strategy with respect to the crop-specific genetic and ecophysiological effects on the formation of phytochemicals.

Crop management strategies of the model crops broccoli, cauliflower and radish demonstrate the possibility to enhance the content of phytochemicals through targeted usage of the ecophysiological factors temperature and irradiation. Thus, the planning of the cultivation period in the annual course combined with the selection of types and cultivars as well at the developmental stage at harvest are the primary means of ensuring consumer-oriented quality production.

For the production of glucosinolate-enriched raw plant material for functional foods or supplements, the cultivation of the green coloured broccoli crown type, e. g. cultivars 'Marathon' or 'Shogun', in the spring season marked by relatively low daily mean temperatures (about 14 °C) combined with rising daily mean irradiation up to 450 μmol m^{-2} s^{-1} of the photosynthetic photon flux density is recommended. Producing key health-promoting glucosinolate groups, e. g. indole glucosinolates, violet broccoli (e. g. cultivar 'Viola'), violet cauliflower (e. g. cultivar 'Rosalind') and green cauliflower (e. g. cultivars 'Alverda' or 'Minarett') should be chosen for cultivation. With progressing head development of broccoli and cauliflower, the glucosinolate content decreased [32]. Thus, incompletely developed broccoli and cauliflower heads should be harvested in respect to glucosinolate-enriched raw plant material. Considering the recent trend to mini vegetables as a new market segment, glucosinolate-enriched mini-broccoli and mini-cauliflower could be created to satisfy this market.

Broccoli could be produced as a fresh market product characterised by a large anti-oxidative potential due to the high carotenoid content as well as being enriched with the anti-oxidatively effective ascorbic acid by selecting the correct time of planting and harvesting. As found for glucosinolates, low daily mean temperatures promoted the syntheses of lutein and β-carotene in broccoli. This temperature effect is also observed for ascorbic acid formation [32]. Moreover, the development stage determines the contents of these compounds [e. g. 32]. To produce broccoli as a fresh vegetable with a high anti-oxidative potential, fully developed heads originated from spring and autumn cultivation sets should be harvested. Cultivation in summer with daily mean temperatures above 20 °C led to a diminution of these anti-oxidatively effective compounds, and therefore should be avoided.

For both the mini-vegetables and fully developed ones, optimised sulphur supply of up to 600 mg S $plant^{-1}$ increased the alkyl and indole glucosinolates which was mainly caused by the enhanced content of glucoraphanin and glucobrassicin [32, 46]. High plant density (97,500 plants ha^{-1}) as well as the reduction of water supply led to increased alkyl glucosinolates – mainly glucoraphanin – however, the yield was reduced simultaneously and the overall proportion of indole glucosinolates was unaffected by reduced plant spacing [32, 44]. Hence, these cultural practices could only have a limited use.

Radish roots enriched with phytochemicals are characterised by enhanced contents of glucosinolates and anthocyanins. In addition, the content of the also health-promoting pectic substances could be increased. For producing anthocyanin-rich radishes, fully coloured red or purple cultivars (e. g. cultivars 'Nevadar', 'Rudi' or 'Sirri') should be chosen first, whereas white (e. g. cultivars 'White Breakfast' or 'Eiszapfen') or half red coloured radish roots (e. g. cultivar 'Flamboyant') showed pronounced reduced levels of anthocyanins. Intensive colouration of the radish periderm indicates enhanced content of anthocyanins which is irradiation- and temperature-dependent [34]. For example, the red colouration of 'Nevadar' radish was most intensive at a relatively high mean of the photosynthetic active irradiation (450 μmol m^{-2} s^{-1}). Simultaneously, lower mean temperatures of around 11 °C caused a more distinctive red shade than higher mean temperatures in the range of 17 °C [40]. Also, the content of indole glucosinolates was amplified at lower mean temperatures with moderate irradiation [38]. The alkenyl glucosinolates were nearly unaffected by these climate conditions. Huyskens-Keil et al. [49] reported that annual accumulation and degradation processes of the also health-protective pectic substances in carrot and radish were strongly dependent on pre-harvest climate regimes. Increasing annual mean temperatures led to an accumulation of pectic substances in radish roots; presumably, due to the enhanced gibberellic acid action as reported for tomatoes [50]. Thus, the cultivation of radishes with high anthocyanins, glucosinolates and pectic substances content should be carried out in spring and late summer. Additionally, the type of soil should be taken into account for consumer-oriented quality radish production. In late summer, sandy soils with a high potential of heat emission should be selected, preventing low indole glucosinolate and anthocyanin contents. For early cultivation in March and April, fleece or films could be used, independent of the soil type, for enhancing the temperature.

As for broccoli, in radish, an optimised sulphur supply of up to 150 mg S plant^{-1} increased the alkenyl glucosinolates, mainly glucoraphasatin [46]. A further possibility for increasing glucosinolates and anthocyanins is the application of elicitors (e. g. amino acids). Applications of amino acids like leucin, phenylalanine or valin as precursers in anthocyanin synthesis also led to rising amounts of anthocyanin in radish [51]. Aliphatic glucosinolates – alkyl and alkenyl glucosinolates – are methionine-derived. Previous experiments demonstrated that the application of methionine led to enhanced glucosinolate contents in radish roots as well as in broccoli heads (Schmidt, Schreiner, Schonhof and Krumbein, unpublished data 2003).

As exemplified by the three model crops, customer-oriented quality production by the targeted usage of genotypic and ecophysiological effects on phytochemicals and other health-promoting compounds is realisable and could serve as a basic framework for other vegetable crops. However, the possibilities of affecting the phytochemical content by crop management strategies greatly vary as demonstrated by the model crops. With respect to the model crops presented here, individual phytochemicals could be increased 10-fold in broccoli and cauliflower [32, 35], and 2-fold in radish [40, 46].

Future prospective

To increase the intake of health-promoting phytochemicals via the consumption of fresh vegetables along with their derived products, the following steps must be taken: 1) Comprehensive monitoring of the pre- and also post-harvest influences on the contents of phytochemicals regarding further important vegetable crops and including also the effect of processing methods; 2) Implementation of well-thought out communication strategies, especially in reaching minorities and low income populations; 3) Development of a thorough and rigorous surveillance plan to monitor vegetable consumption within the population related to psychosocial and economic factors; and 4) Assessment of the environmental influences on dietary behaviour and behaviour change of children and adults. The investigations of genotypic and ecophysiological effects on the formation of phytochemicals in the three selected model crops are just a module for a systematic research approach in respect to the above-mentioned research field. The results of these studies would serve as a key asset of the framework from which further research has to be performed not only in the field of horticulture but also in those of medicine, ecothrophology and nutrition.

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